Labs21 Advanced Course Series

Advanced Exhaust Dispersion Design

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CPP

Goal: Develop an advanced exhaust dispersion design

Objectives: At the end of the session, you will be able to:

- **Implement a balanced design process that considers safety, energy efficiency, aesthetics and other parameters**
- **Distinguish between standard, good and better practice to analyze and address safety of exhaust dispersion**
- **Implement energy efficiency features in exhaust dispersion**

Outline

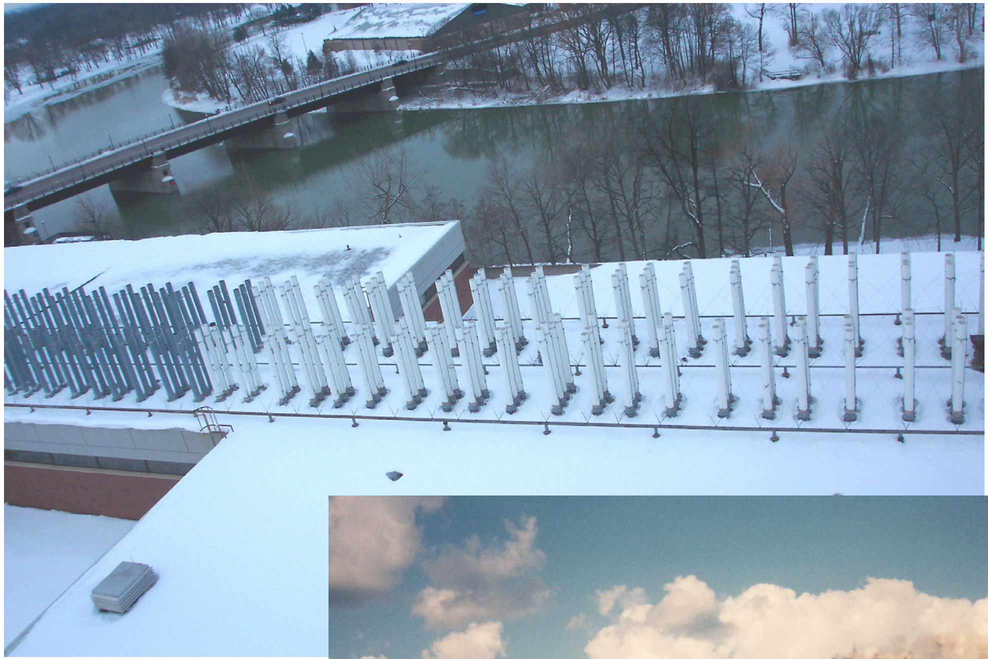
- Introduction
- Process Description
- Standard Practice
- Good Practice
- Better Practice
- Performance Comparison
- Conclusion

Introduction

- **Why is this important?**
  - Beyond worker safety
  - Identify energy efficiency opportunities
- **What is exhaust dispersion design?**
  - Air flow around the building: Spot potential air quality problems
  - Design practice: Know what methods are available
  - Recommended approach: Develop design skills

Stack Design Challenges

- Aesthetics
- Equipment cost
- Noise and vibration
- Structural loads
- Energy costs
- Dispersion modeling



Process Description

Programming

1. **Review Design Intent Document**

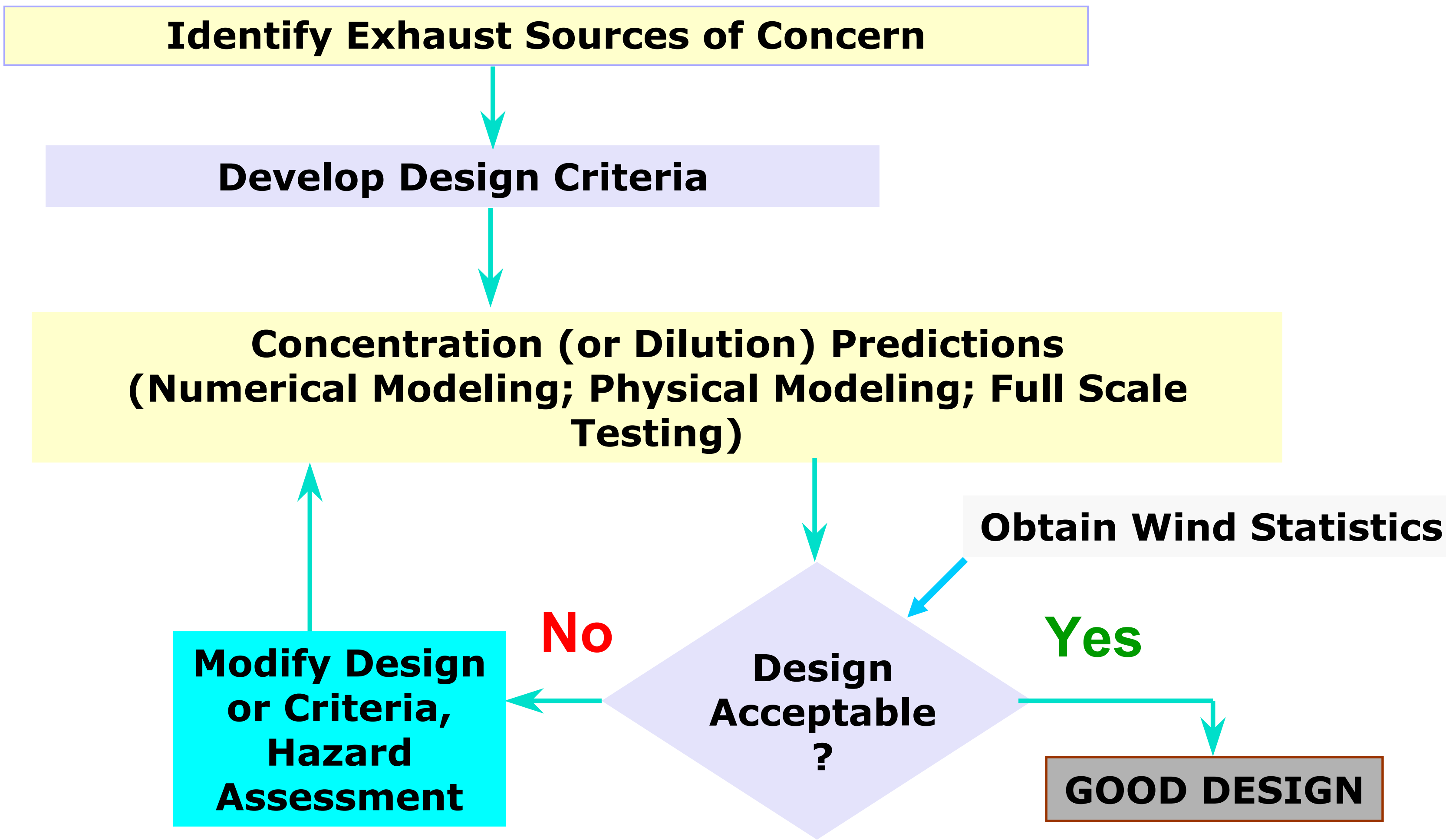
Schematic Design

2. **Determine Level of Design Support**
3. **Identify Sources of Concern**
4. **Develop Concentration Design Criteria**
5. **Predict Concentrations: Apply Design Practice**

Design Development

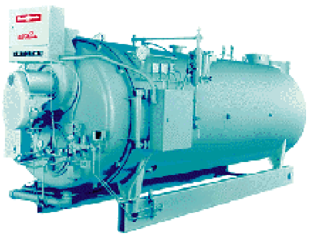
6. **Develop System Design: Apply Design Practice**
7. **Finalize Exhaust Dispersion System Design**

Recommended Approach



Identify Sources of Concern

Boiler

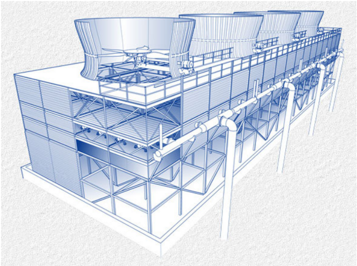


Radioisotope

Biosafety Cabinet
&
Isolation Room

Chemical Fume Hood

Cooling Tower



Animal Room

Traffic

Helicopter

Diesel Vehicles

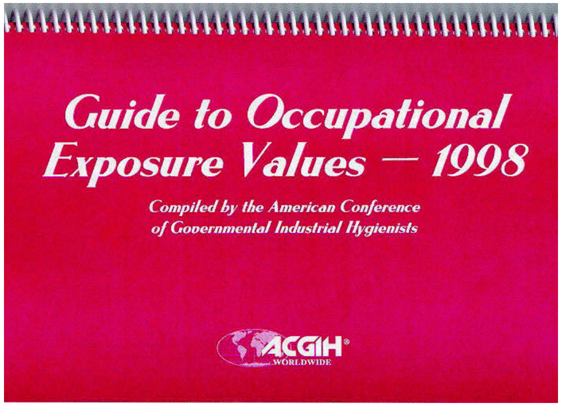
Emergency Generator

Develop Concentration Design Criteria

- **Obtain Hazard Information:**
  - Concentration per unit volume and a mass flow rate for each substance
- **Apply evaluation method**
  - Dilution
    - Easy to visualize
    - Must account for exhaust device's changing internal volume flow
  - Mass emission (normalized concentration)
    - Use mass emission rate (g/s) and health limit in $\mu g/m^3$ to normalize exposure
- **Determine $(C/m)_{health/odor}$ or Dilution $(C/C_o)_{health/odor}$ thresholds**
  - **C_{health}** & **C_{odor}** (concentration per unit volume) for each substance
  - Maximum **m** (mass flow rate) or exhaust concentration (C_o) for each substance

Use Concentration Guidelines

- **Health Limit concentrations** (**C_{health}**)
  - Lowest of ACGIH, OSHA and NIOSH
    - STELs (15 Minute Averaging Time)
    - 8 hr TWA (time weighted average) multiplied by **3**
  - Safety Factor
  - 5 for routine and 1 for accidents (ANSI/AIHA Z9.5 – 2003)
- **Odor Thresholds** (**C_{odor}**)
  - ACGIH; various research



Predict Concentrations: Apply Design Practice

- **Standard Design Practice**
  - Use Prescriptive Design Guidelines
- **Good Design Practice**
  - ASHRAE and EPA Calculation and Graphical Methods
  - Plume Dispersion calculations
- **Better Design Practice**
  - Computational Fluid Dynamics
  - Wind Tunnel Modeling

Standard Design Practice

- **Safety Considerations**
  - Apply International Mechanical Code (IMC) or Uniform Mechanical Code (UMC)
  - Use EPA, ASHRAE prescriptive guidelines for stack exit velocity and location.

- **Energy efficiency features**
  - None

Design Codes: Requirements

- **IMC & UMC**
  - Exhaust system shall discharge at a point where it will not cause a nuisance and from which it cannot be readily drawn in by a ventilating system
  - Exhaust ducts discharging other product (heat, odors, smoke, etc.) shall terminate:
    - 1) 10 ft from the property line;
    - 2) 3 from from exterior walls and roofs;
    - 3) 10 ft from openings into the building; 10 ft above adjoining grade.
  - Exhaust ducts discharging explosive or flammable vapors shall terminate:
    - 1) 30 ft from the property line;
    - 2) 10 ft from openings into the building;
    - 3) 30 ft from combustible walls and openings in the building;
    - 4) 10 ft above adjoining grade.

Prescriptive Design Guidelines: Design Strategies

– from ASHRAE HVAC Applications, Chapter 44, 2003

- Includes exhaust stack velocity guidelines
- Suggests increasing stack height or separation distance
- Recommends locating on tallest building feature
- Requires vertically directed stack with no caps
- Provides other stack design standards

Prescriptive Design Guidelines: Stack Velocity

- **Maintain exit velocity V_e above:**
  - 10 m/s unless droplets in exhaust stream; then use 5 m/s. (ASHRAE 2003, Chapter 44)
  - 15.2 m/s unless lower velocity demonstrated adequate. (ANSI/AIHA Z9.5 – 2003)
  - 1.5 times the 1 % wind speed at stack top (ASHRAE 2003, Chapter 44).

Prescriptive Design Guidelines: Stack Height

- **ANSI/AIHA Standard Z9.5 – 10 ft above adjacent roof line**
- **Standard NFPA 45 – minimum 10 ft height to protect rooftop workers**
- **NFPA 92A – exhaust stack discharge location should be away from building outside air intakes to minimize recirculation**
- **EPA - GEP stack height (2.5 times the building height)**

Prescriptive Stack Design Summary

- Reduce source emissions
- Determine stack height
- Provide adequate exit velocity
- Maximize plume height
- Locate on similar building heights
- Position intakes low, but avoid street level

Good Design Practice

- **Safety considerations**
  - Stack design strategies
  - Analytical dispersion methods
  - Graphical dispersion methods
- **Energy efficiency features**
  - Stepped CV fan operation
  - Consider VAV air exhaust devices

Stack Design Strategies

- Central exhausts with combined flows
- Ganged stacks
- Reduce contamination with filters, collectors and scrubbers
- Entrained air stacks

Analytical Dispersion Methods

- Based on plume dispersion estimations.
- Applicable for simple buildings with no taller surrounding buildings/features with air intakes on the building roof.
- Experienced professional can develop conservative exhaust designs.
- Method may not be conservative if used by inexperienced practitioner.
- Concentration estimates on building sidewalls highly inaccurate.

EPA and ASHRAE Plume Dispersion

- Gaussian Diffusion Equation
- Plume Rise calculation
- Horizontal Dispersion Coefficients
- Vertical Dispersion Coefficients
- Wind Speed considerations

EPA Dispersion Equation

$$\frac{C}{m} = \frac{1}{\{\pi\,\sigma_y\,\sigma_z\,U_s\}}\exp[-\frac{h^2}{2\,\sigma_z^2}]\,x\,10^6$$

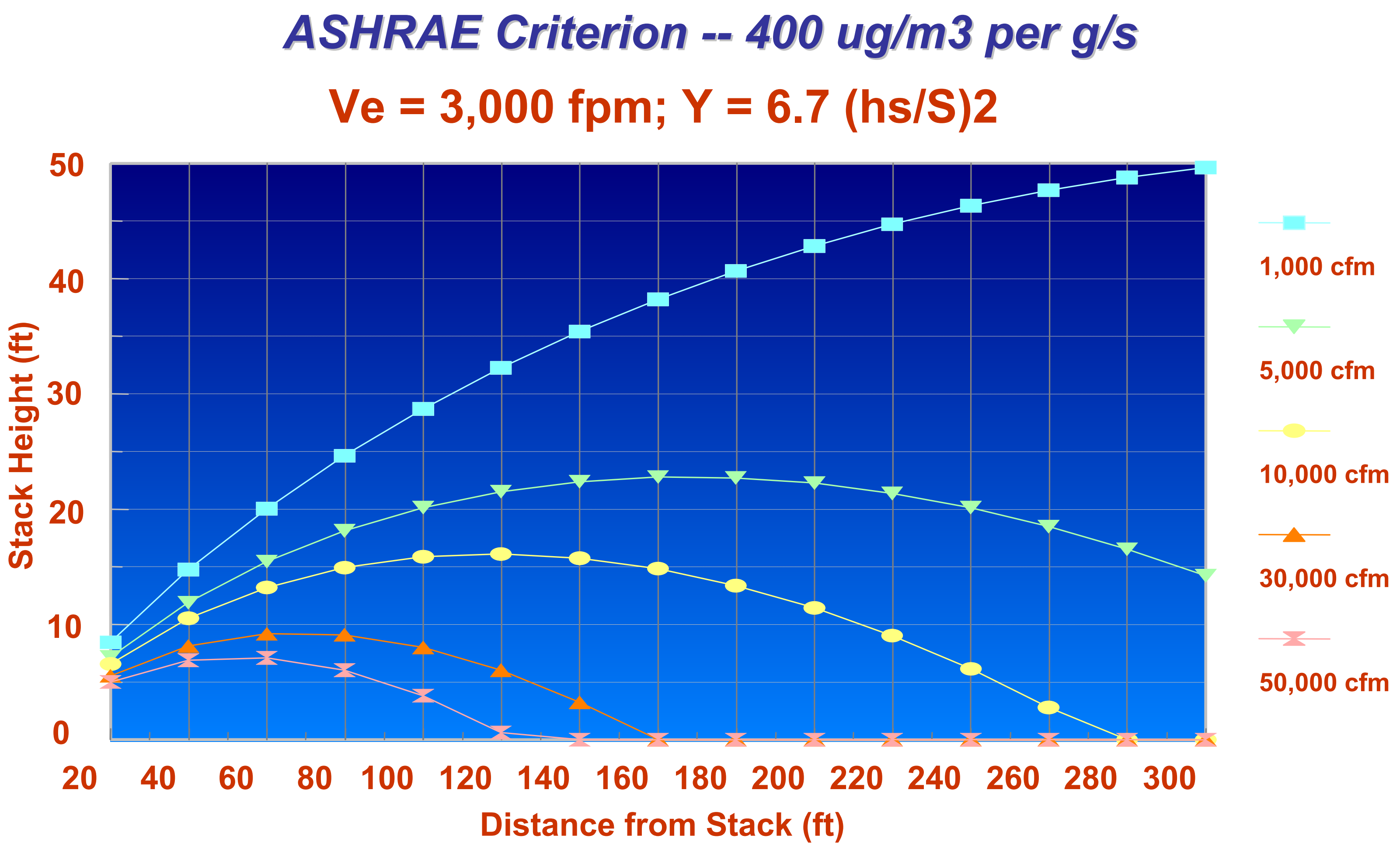
ASHRAE Plume Dispersion (at roof level)

$$D_r = 4\frac{U_H}{V_e}\frac{\sigma_y}{d_e}\frac{\sigma_z}{d_e}\exp\left(\frac{h^2}{2\sigma_z^2}\right)$$

$$\frac{h^2}{2\sigma_z^2} < 5.0$$

$$(i.e., h < 3.16\sigma_z)$$

Initial Stack Height Design Chart



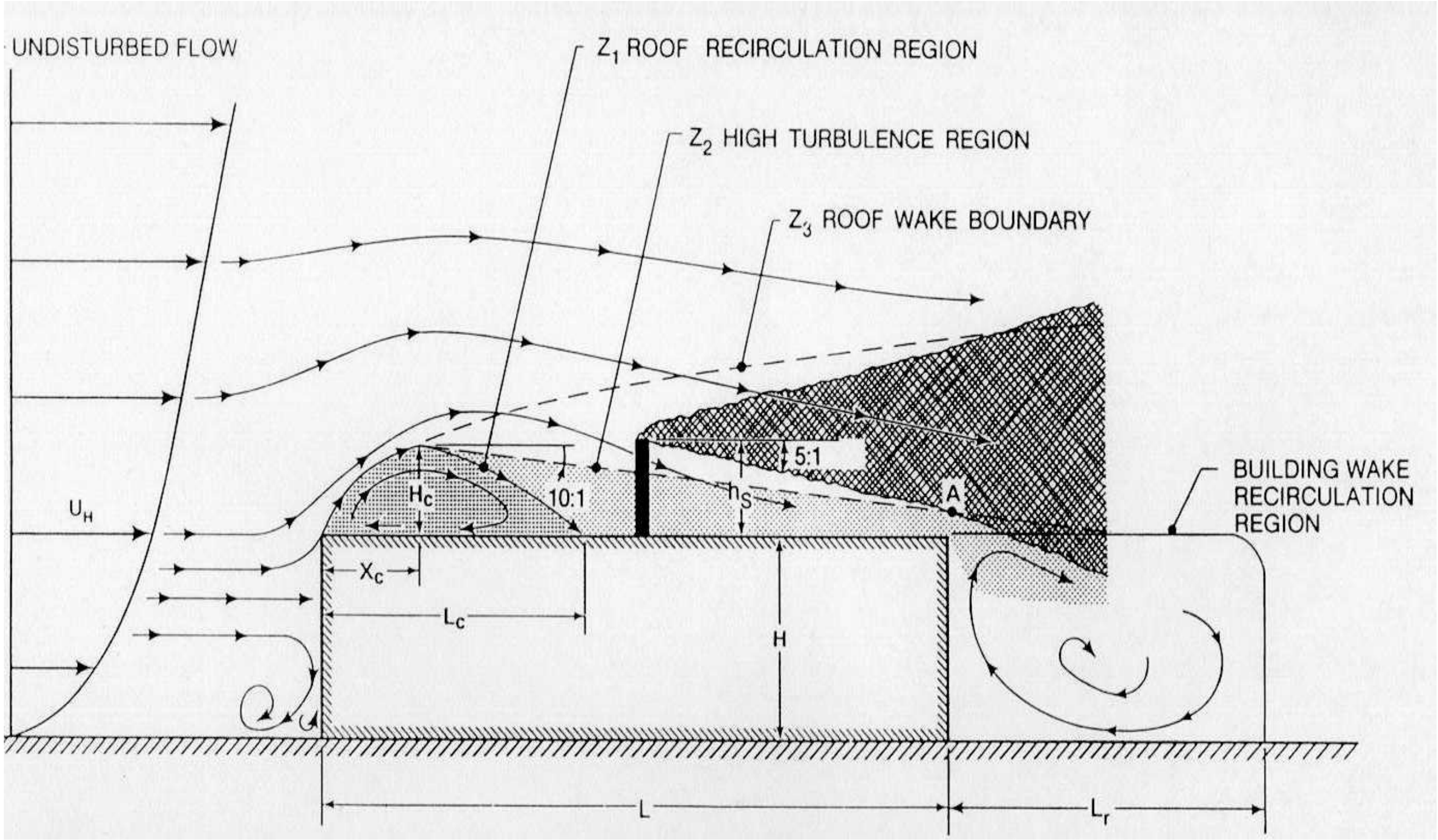
Graphical Dispersion Method

- Method should prevent fume reentry into emitting building most of time.
- Not recommended when taller buildings or terrain are nearby or when exhaust contains toxic gases.
- Concentration calculations recommended if excessively tall stacks are estimated or if exhaust contains toxic gases.

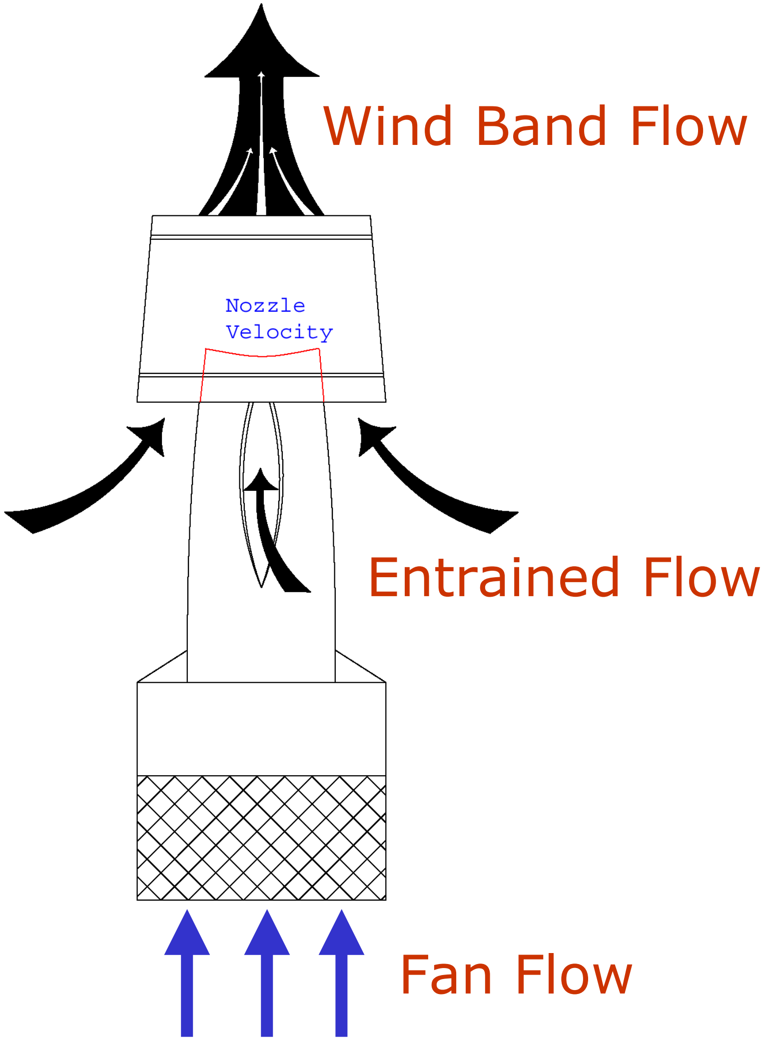
Graphical Method…

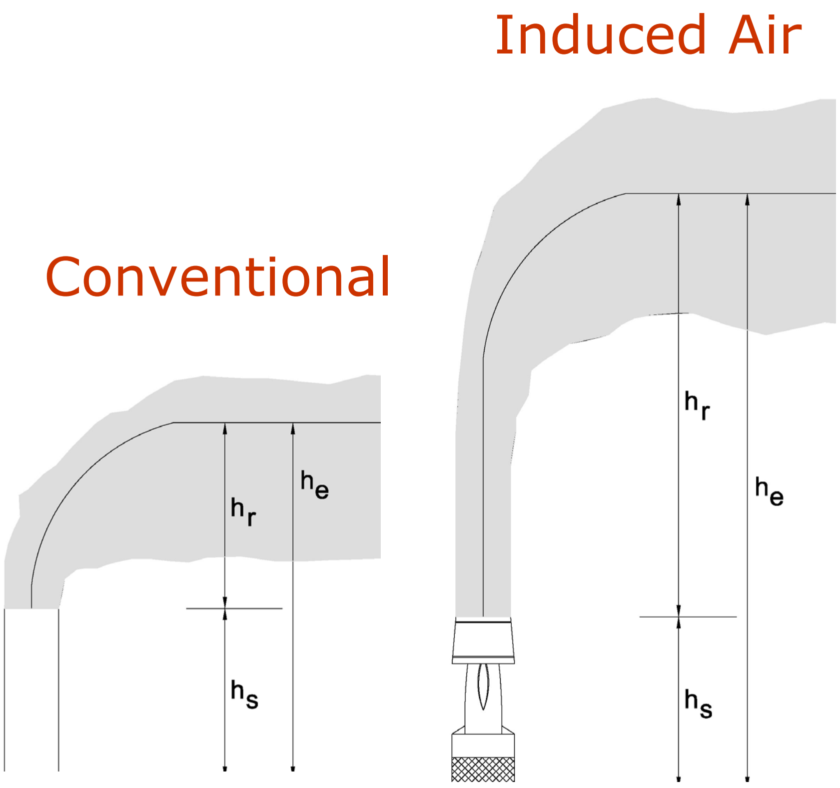
- Step 1 – estimate height and location of flow re-circulations
- Step 2 – estimate required height for capped stack
- Step 3 – reduce required height based on plume rise.

ASHRAE Graphical Method

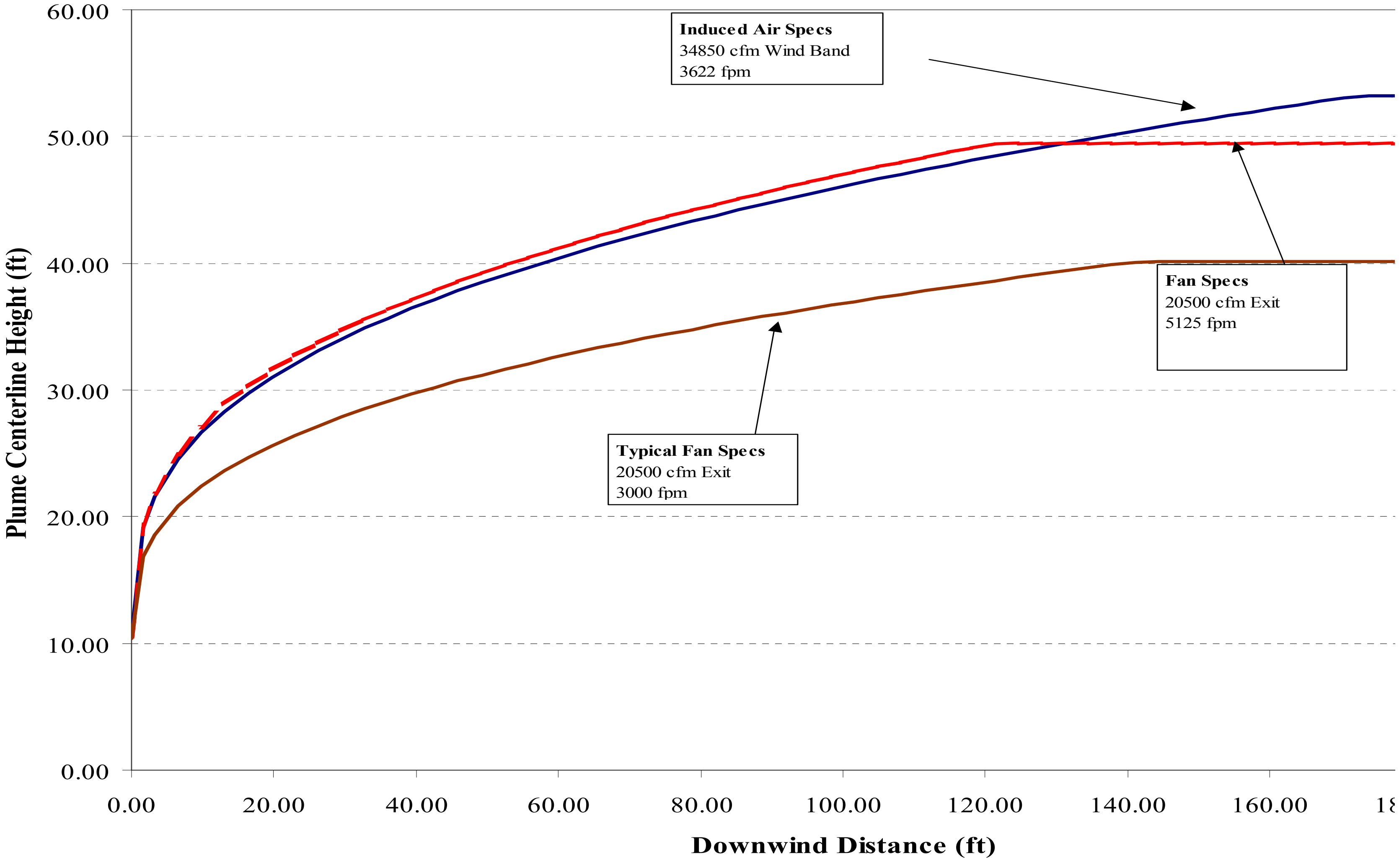


Induced Air Fans: verify plume rise





Conventional vs. Entrained Air – 20 mph



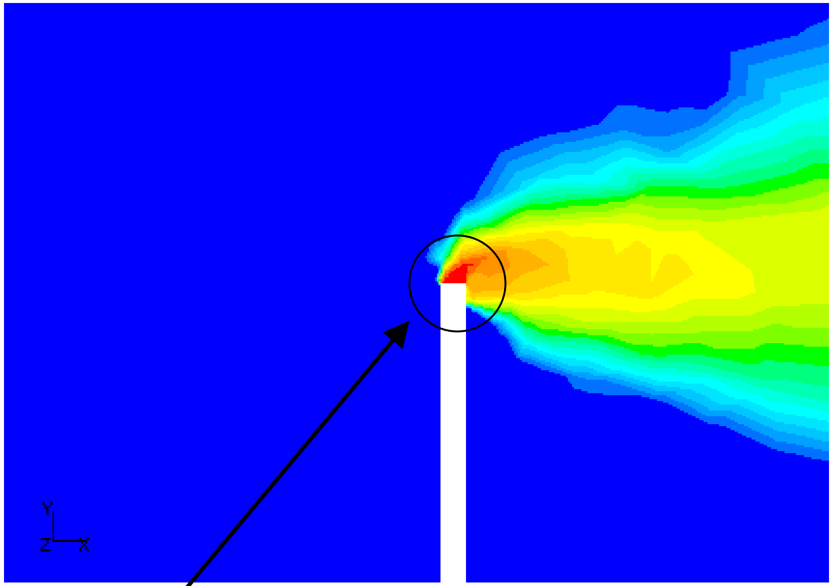
Better Design Practice

- **Safety considerations**
  - Computational Fluid Dynamics (CFD) review
  - Wind-tunnel (WT) modeling
- **Energy efficiency features**
  - Variable Air Volume (VAV) system
  - Real-time wind monitoring

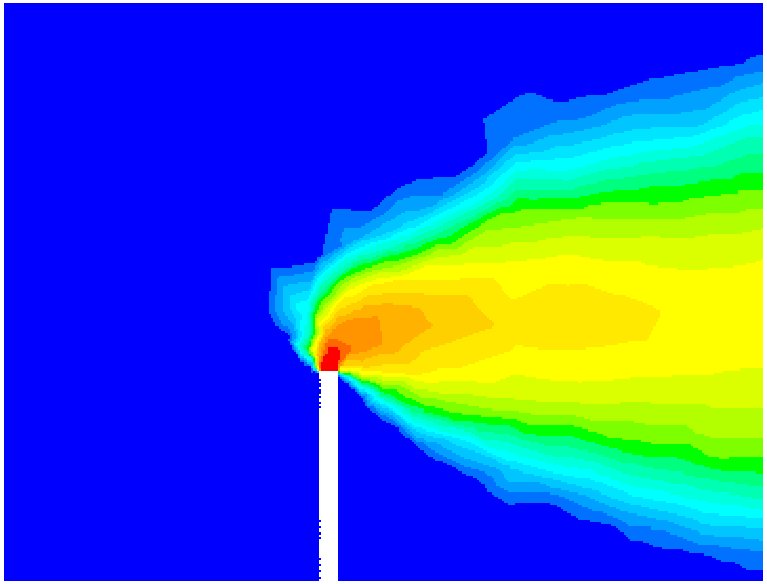
CFD and Wind Tunnel Comparison

- **Have basic equations of motion been solved?**
  - CFD: yes, but turbulence closure is approximate
  - WT: yes, turbulence is accurately modeled
- **Have field (empirical) databases been validated?**
  - CFD: ?
  - WT: yes; used to validate CFD and analytical techniques
- **Have atmospheric dispersion comparisons been demonstrated?**
  - CFD: ? , but EPA is working on these comparisons
  - WT: yes
- **Is there a standard method of application?**
  - CFD: no. EPA is working on this
  - WT: yes. EPA has guidelines
- **Are conservative estimates provided?**
  - CFD: ?
  - WT: yes

CFD Plume Rise Simulation



Velocity ratio 0.5, Flagging is evident to right of stack



Velocity ratio 2.3, no flagging

Computational Fluid Dynamics (CFD): External Flow Summary

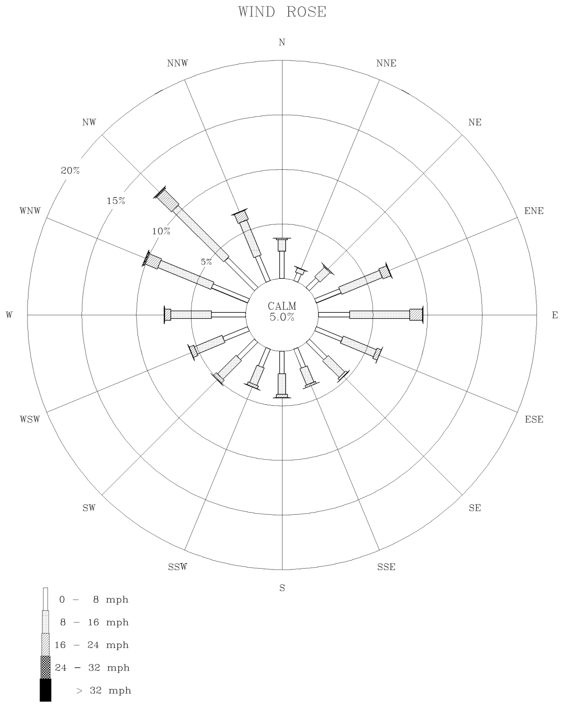
- Future state of the art
- Turbulence closure a problem
- No standard user methods
- Not yet suitable in complex outdoor environment

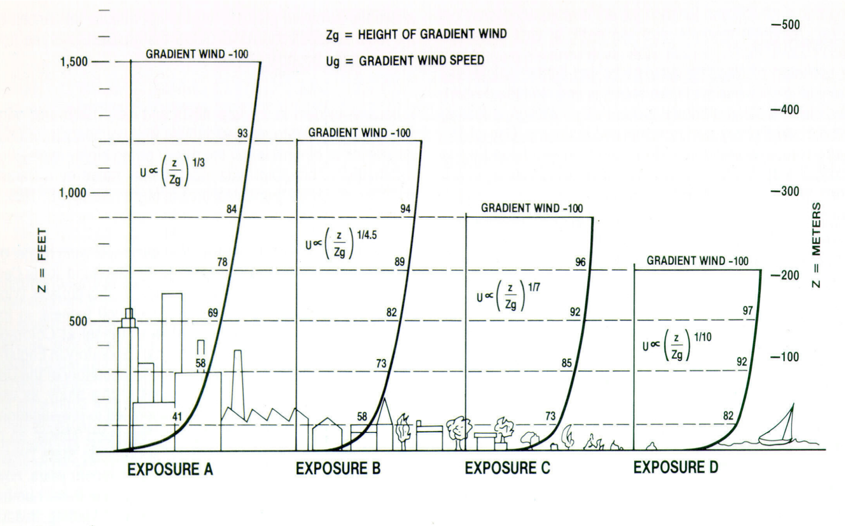
Wind Tunnel Modeling: Overview

- Match Velocity Ratio
- Match Density Ratio
- Scale all dimensions by common factor
- Use with high Reynolds Numbers
- Apply wind velocity and turbulence profiles
- Simulate exhaust airflow temperature and buoyancy

Wind Tunnel Modeling: Process Steps

- Specify model operating conditions
- Construct scale model
- Setup and visualize dispersion
- Measure concentrations
- Compare results with design criteria



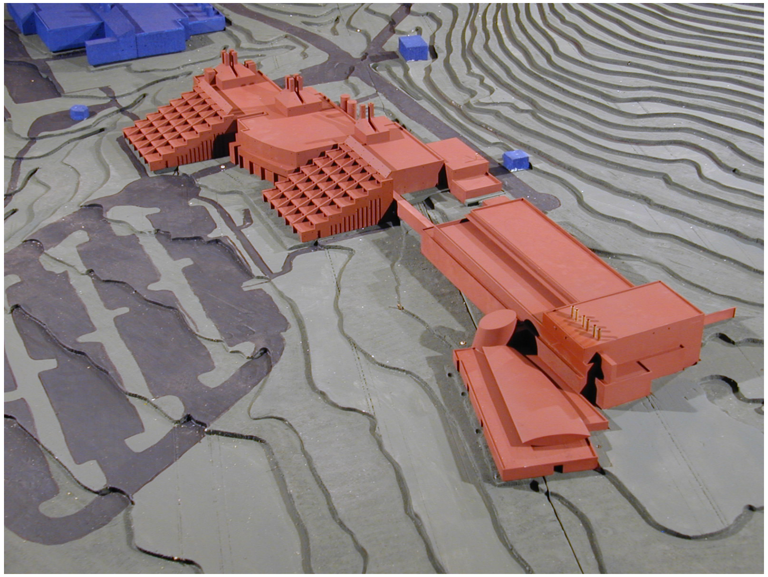


Typical Source Parameter Table…

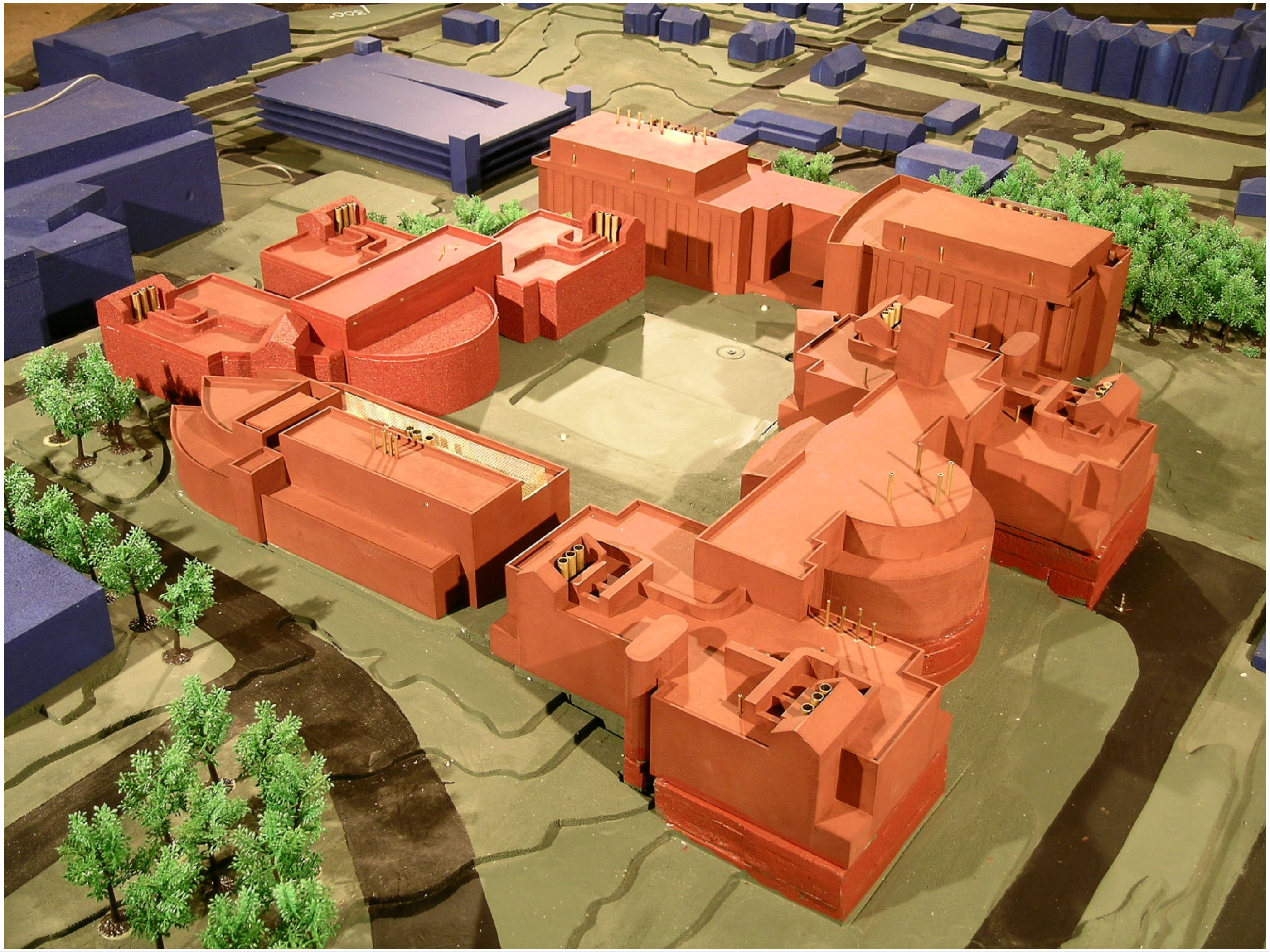
Source Description	Stack ID	Initial Stack Height Above Grade (ft)	Exit Diameter (in)	Exit Temperature (^oF)	Volume Flow Rate (cfm)	Exit Velocity (fpm)
1 Fume Hood Exhaust	EF	20.0	62.0	72.1	66,000	3148
2 Kitchen Exhaust	KE	3.0	29.7	72.1	12,000	2500
3 Loading Dock	LD	10.0	4.0	300.0	200	2292
4 500 KW Diesel Generator	DG	4.0	8.0	1119.2	4,301	12321
5 Cremator Exhaust	CE	25.0	24.0	72.1	4,712	1500
6 Air Handling Unit	AHU	4.0	239.9	72.1	65,000	207

Wind Tunnel Modeling: Process Steps

- Specify model operating conditions
- Construct scale model
- Setup and visualize dispersion
- Measure concentrations
- Compare results with design criteria



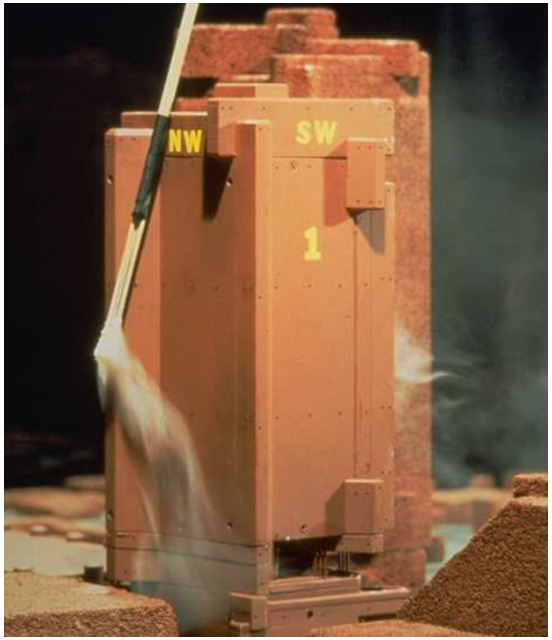
Model from the SE

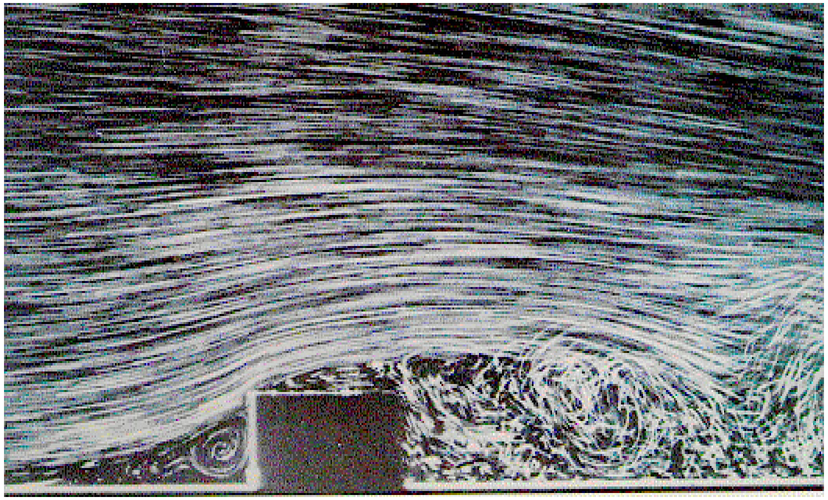


University lab models in wind tunnel

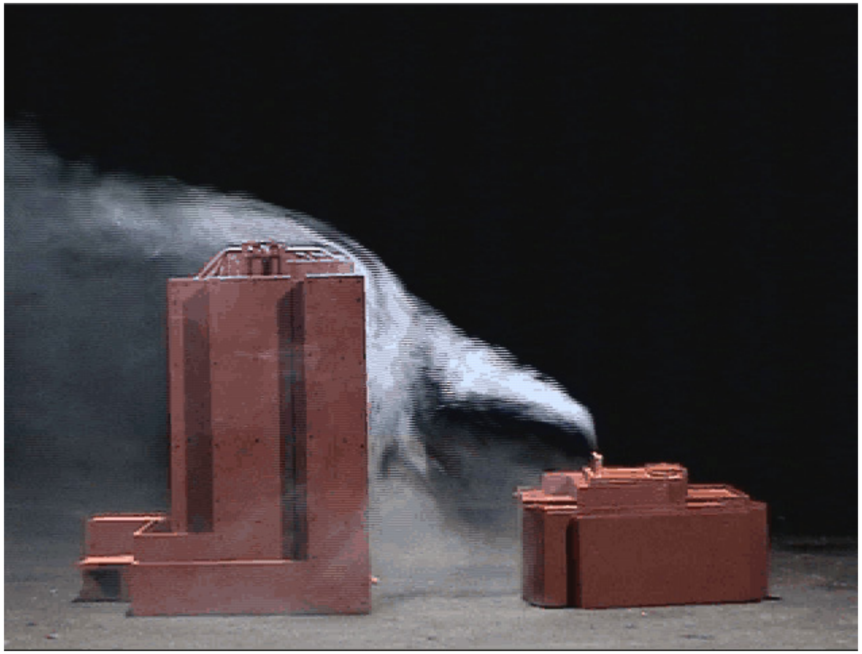
Wind Tunnel Modeling: Process Steps

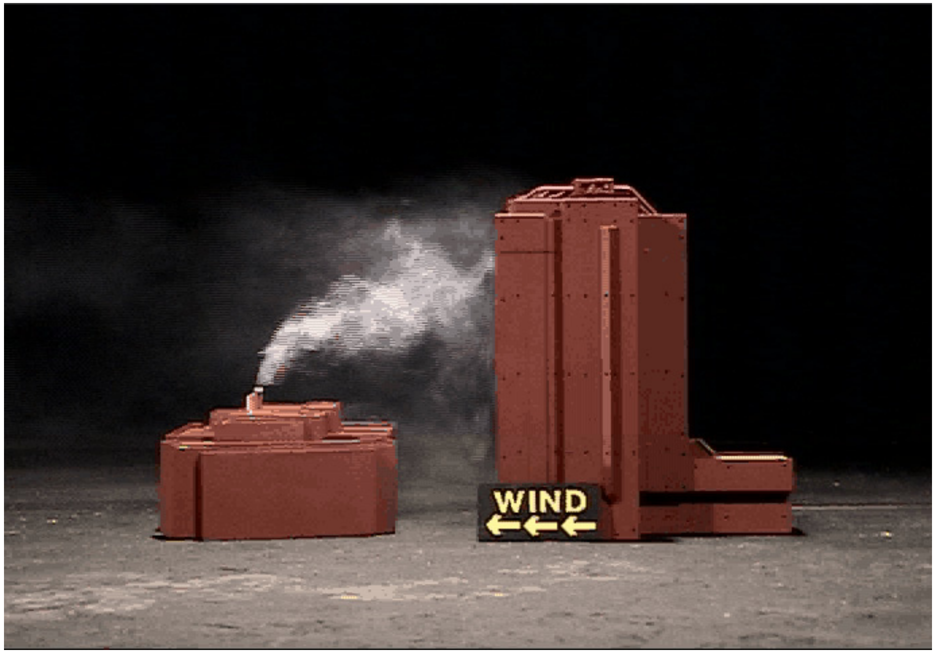
- Specify model operating conditions
- Construct scale model
- Setup and visualize dispersion
- Measure concentrations
- Compare results with design criteria





Visualizing Dispersion



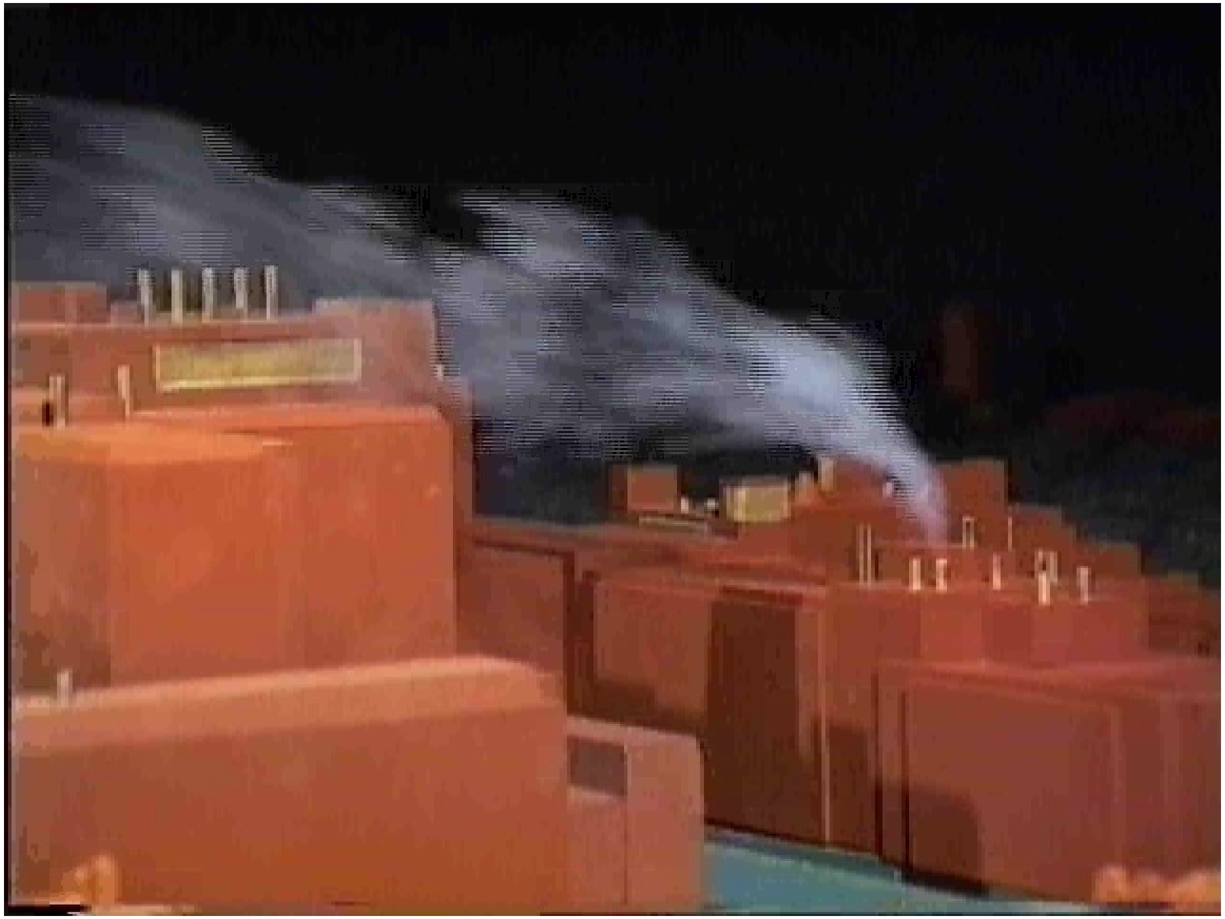


Wind Tunnel Modeling: Process Steps

- Specify model operating conditions
- Construct scale model
- Setup and visualize dispersion
- Measure concentrations
- Compare results with design criteria

Measuring Dispersion

Tracer from stack



Sample withdrawn from intake

Example 1:

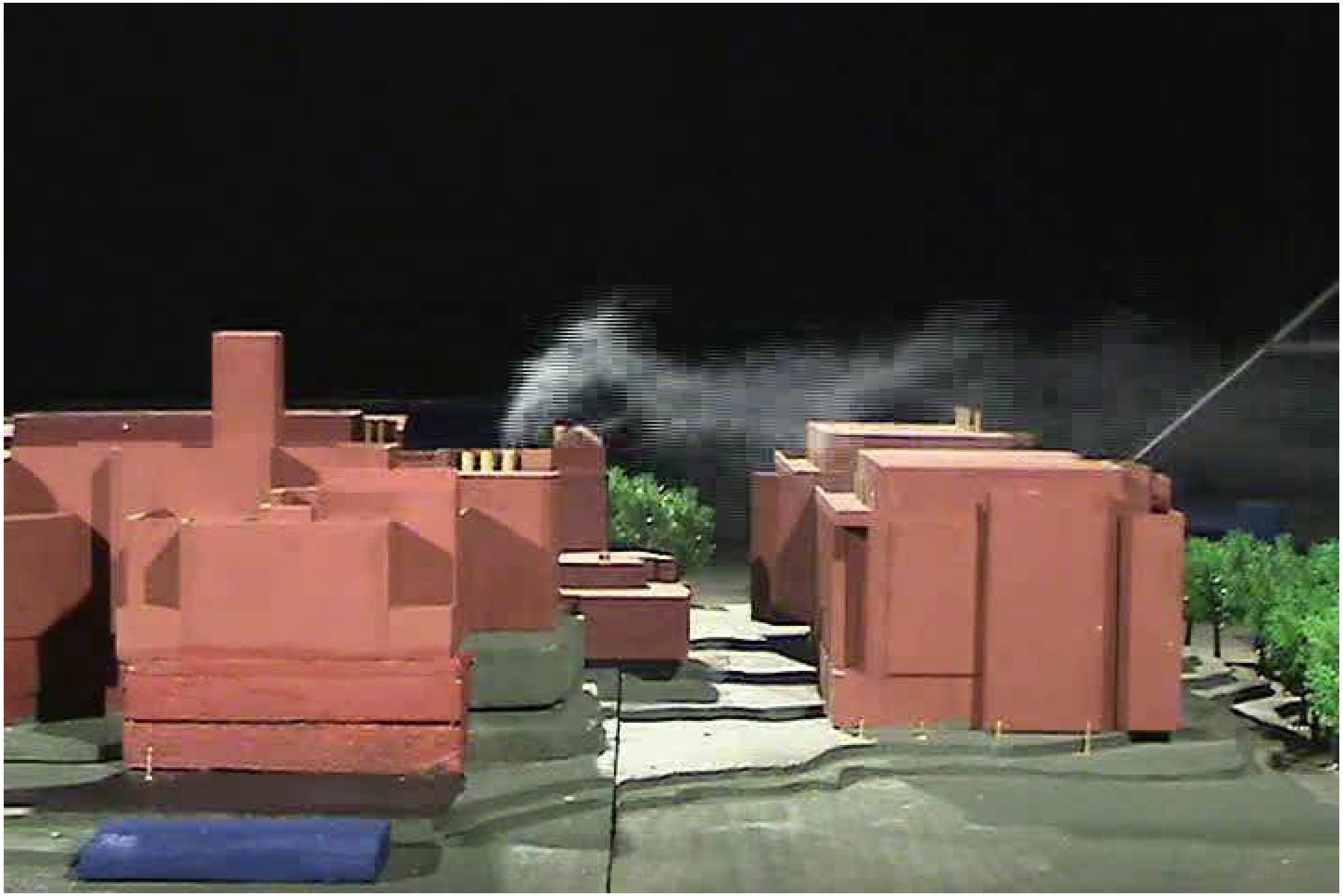
H_s = 18.3 ft, $(C/m)_{max}$ = 285; Criteria = 400

Example 2:

H_s = 18.3 ft, $(C/m)_{max}$ = 234; Criteria = 400

Example 3:

H_s = 18.7 ft, $(C/m)_{max}$ = 141; Criteria = 400



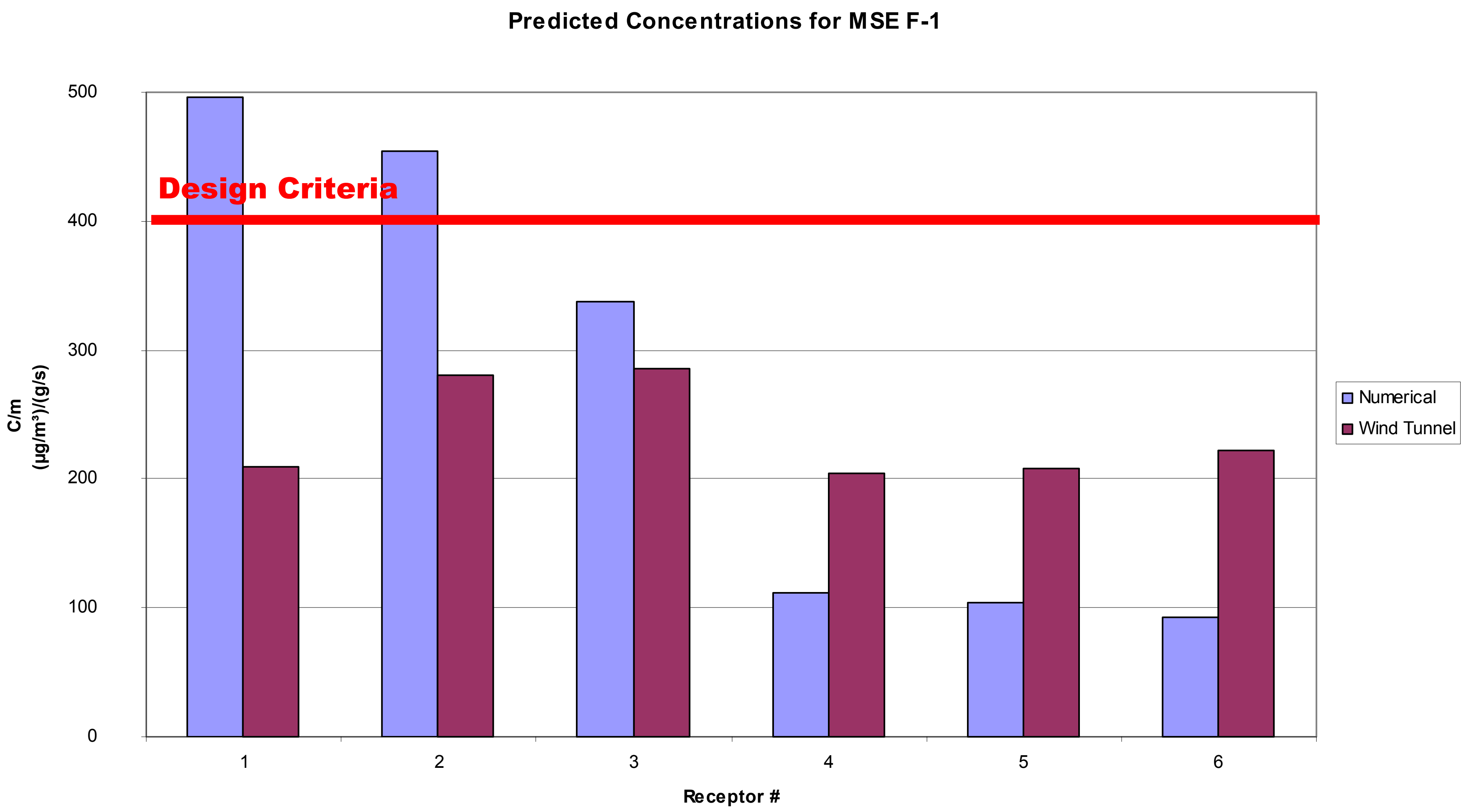
Example 4:

H_s = 3 ft, $(C/m)_{max}$ = 5741; Criteria = 2293

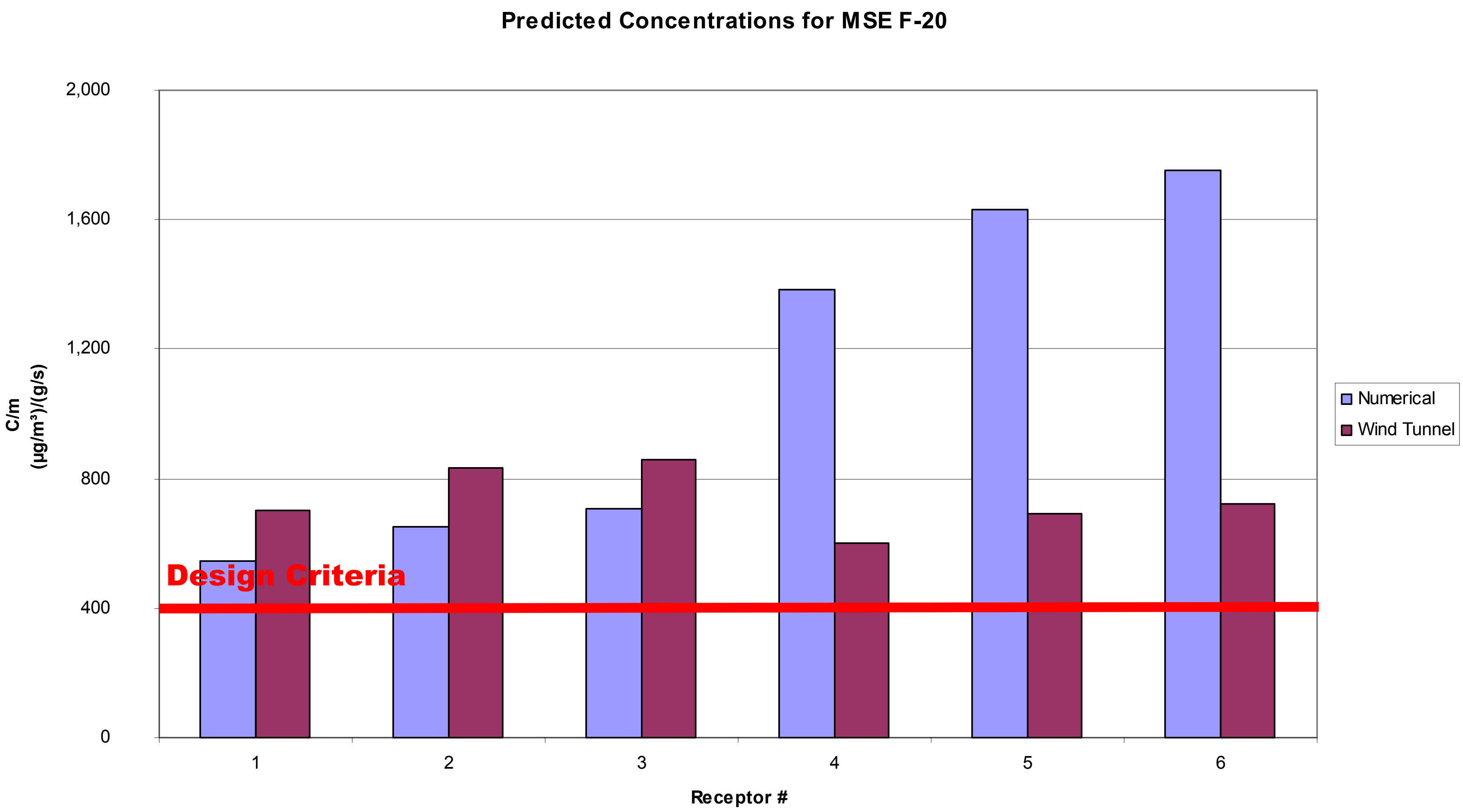
Wind Tunnel Modeling: Process Steps

- Specify model operating conditions
- Construct scale model
- Setup and visualize dispersion
- Measure concentrations
- Compare results with design criteria

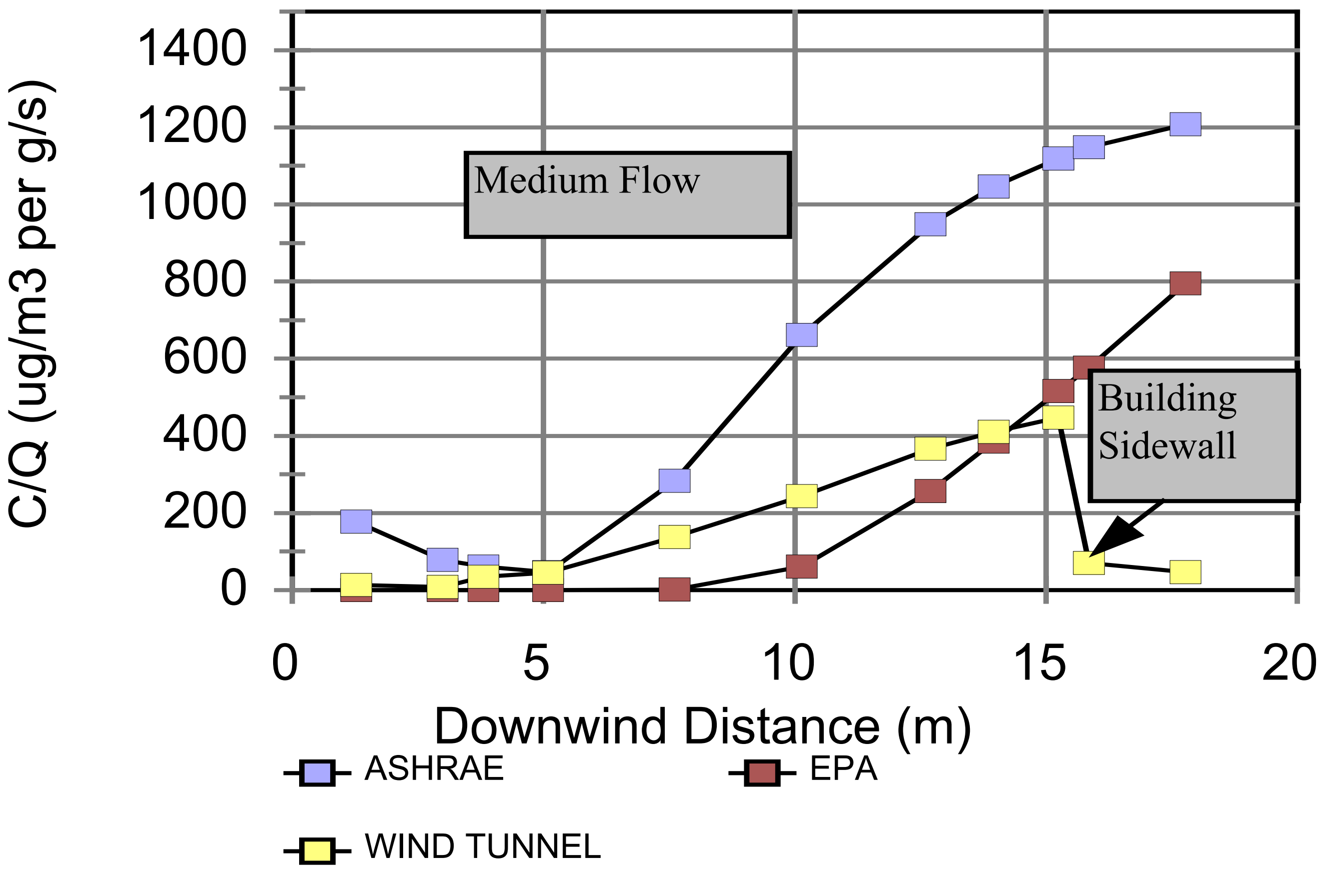
WT vs. Numerical - MS&E Lab Exhaust



WT vs. Numerical - MS&E Lab Exhaust

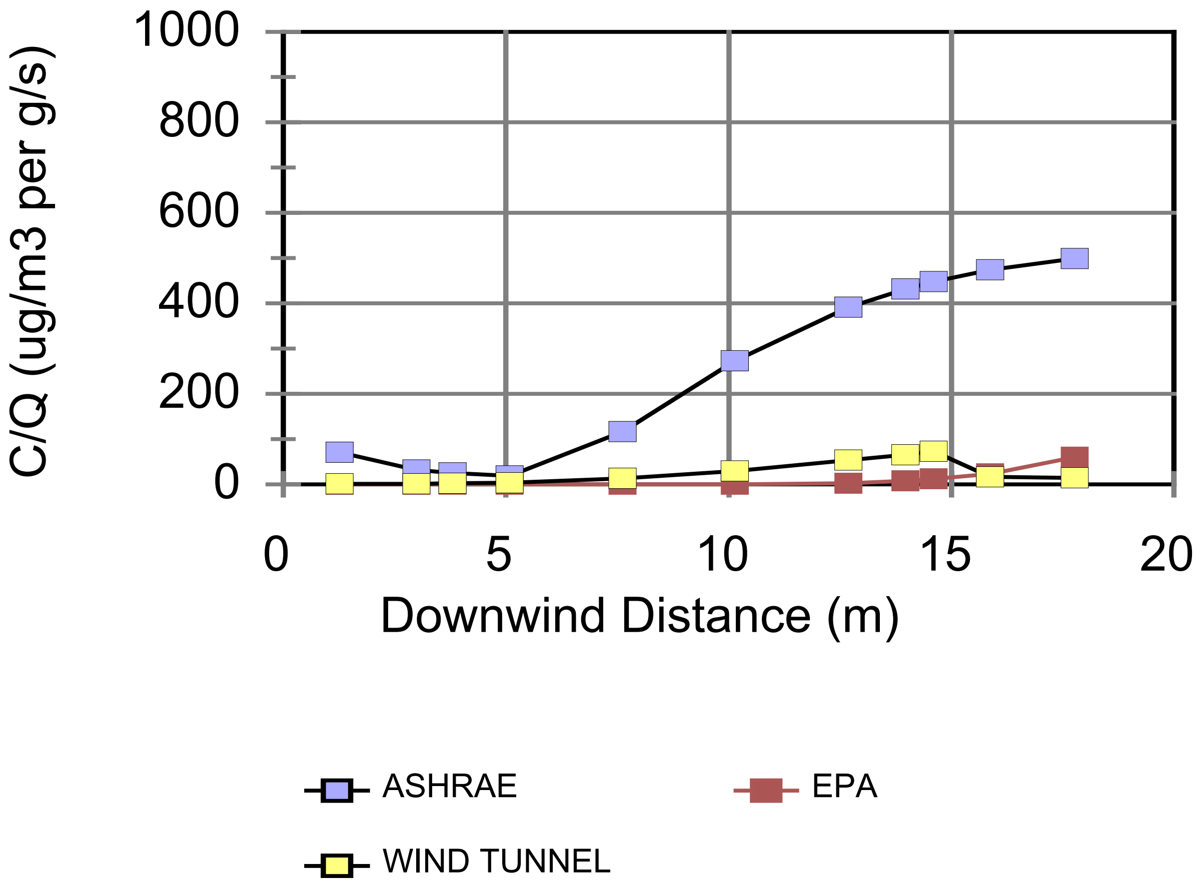


ASHRAE, EPA and Wind Tunnel
Medium Flow Stack

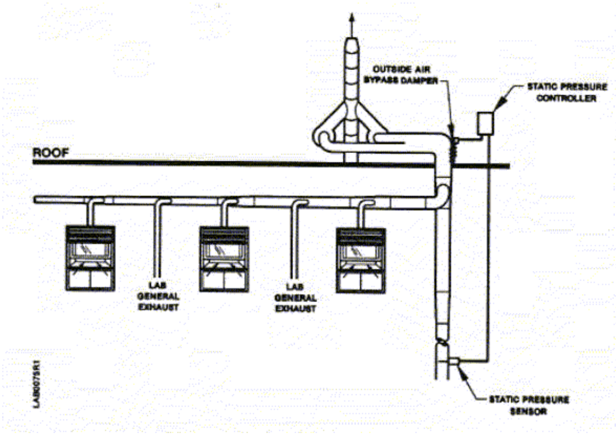


ASHRAE, EPA and Wind Tunnel

High Flow Stack



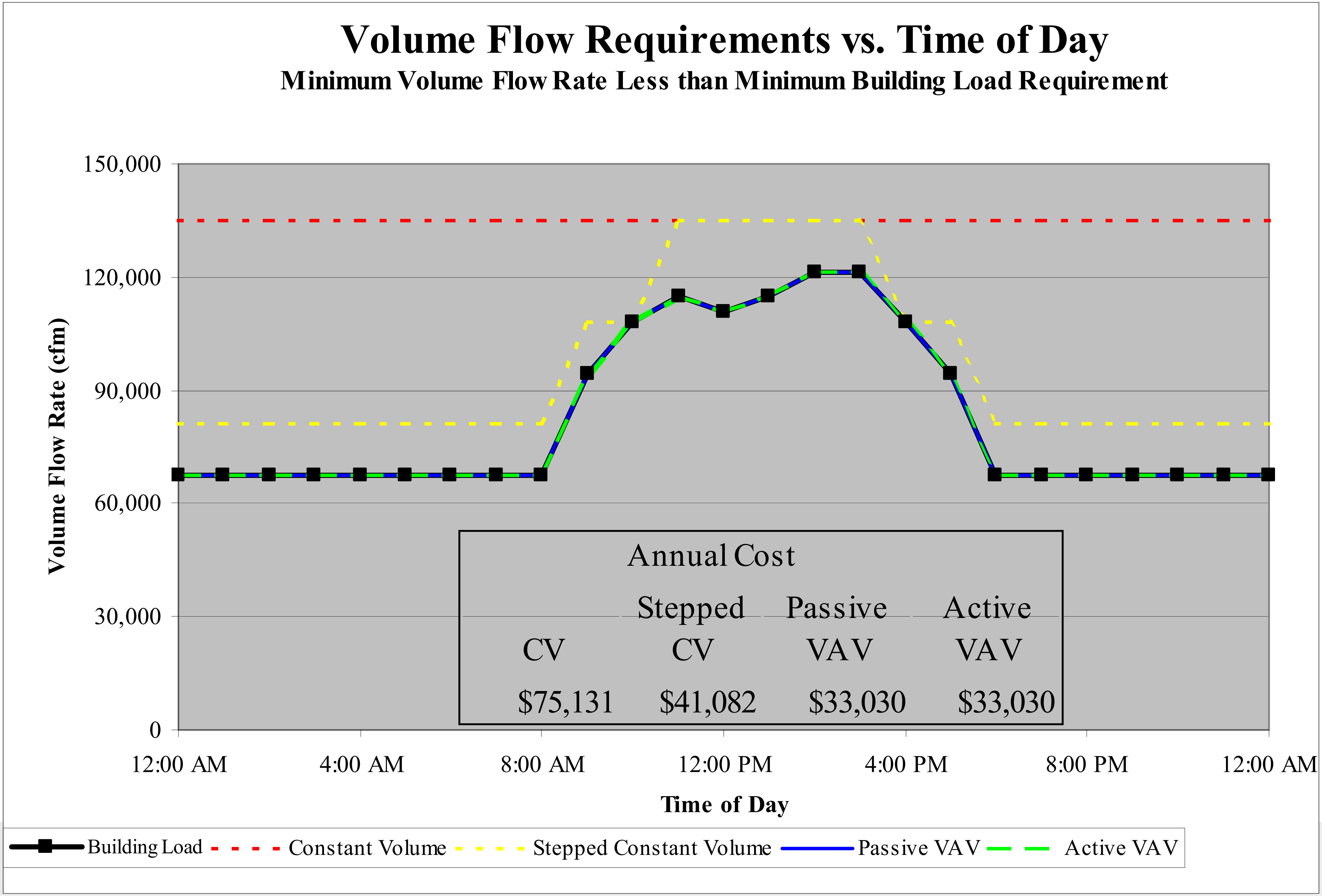
Energy Efficiency Performance Comparison



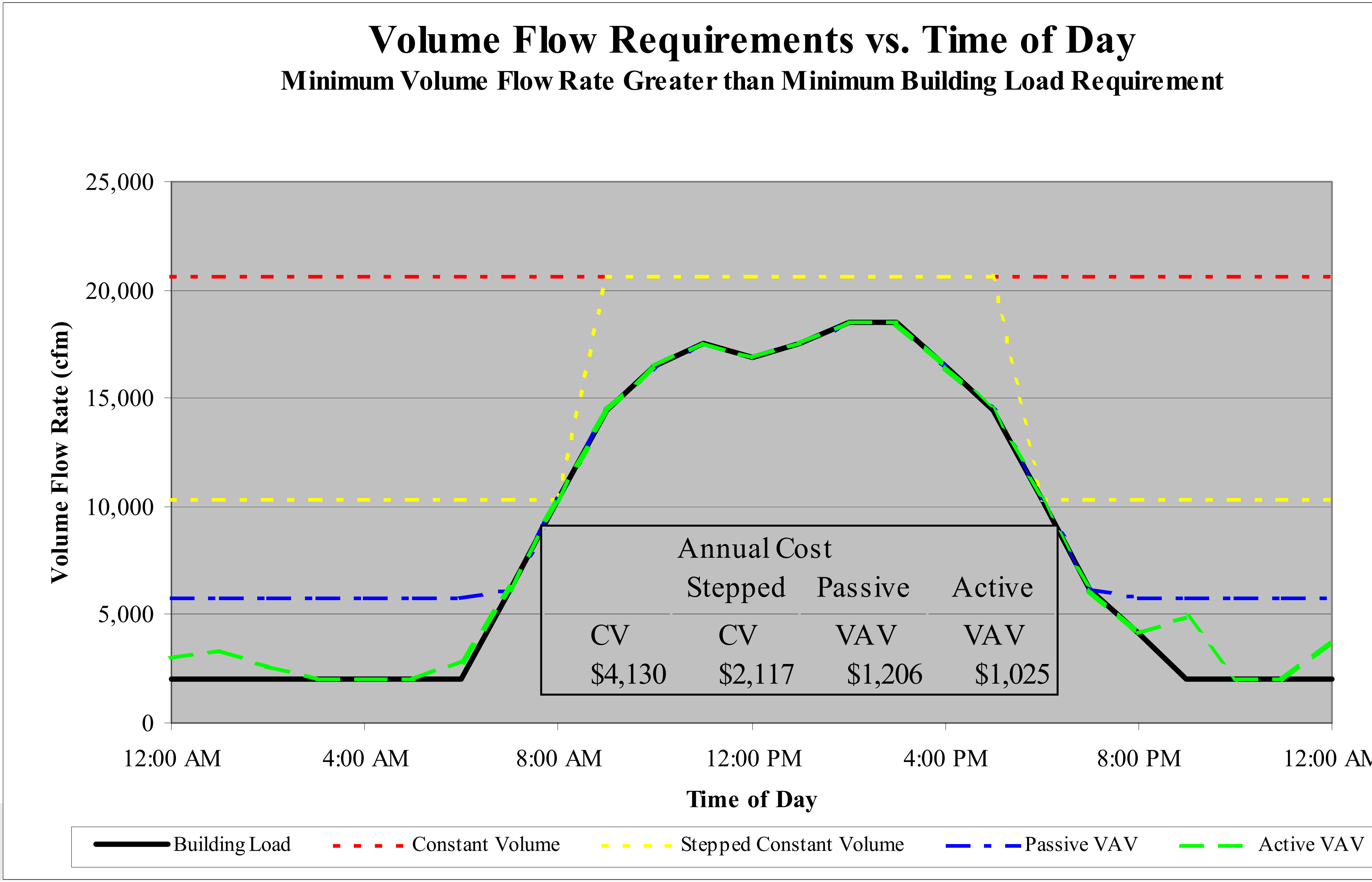
- **Standard Practice**
  - Baseline energy consumption
  - Constant volume (CV) exhaust system
- **Good Practice**
  - Stepped CV fan operation
  - Consider entrained air exhaust devices
- **Better Practice**
  - Variable air volume (VAV) exhaust system
  - VAV with real-time wind data input

Energy Efficiency Modes of Operation

- CV – constant volume to meet maximum building load requirement
- Stepped CV – staged fans operating to meet hourly building load
- Passive VAV – no met tower, meet building load or minimum safe flow for AQ
- Active VAV – meteorological tower provides real-tame wind data input, meet building load and minimum flow by hour for acceptable AQ



Volume Flow Requirements vs. Time of Day
Minimum Volume Flow Rate Less than Minimum Building Load Requirement
150,000
120,000
90,000
60,000
30,000
0
Volume Flow Rate (cfm)
Annual Cost
CV
Stepped CV
Passive VAV
Active VAV
$75,131
$41,082
$33,030
$33,030
12:00 AM
4:00 AM
8:00 AM
12:00 PM
4:00 PM
8:00 PM
12:00 AM
Time of Day
Building Load
Constant Volume
Stepped Constant Volume
Passive VAV
Active VAV



Volume Flow Requirements vs. Time of Day
Minimum Volume Flow Rate Greater than Minimum Building Load Requirement
Volume Flow Rate (cfm)
25,000
20,000
15,000
10,000
5,000
0
12:00 AM
4:00 AM
8:00 AM
12:00 PM
4:00 PM
8:00 PM
12:00 AM
Time of Day
Annual Cost
Stepped
Passive
Active
CV
CV
VAV
VAV
$4,130
$2,117
$1,206
$1,025
Building Load
Constant Volume
Stepped Constant Volume
Passive VAV
Active VAV

Conclusion

- **Design Mission a Success...?**
  - Increased lab safety and efficiency
  - Advanced exhaust dispersion design; predict concentrations
  - Minimized energy waste
  - Provided optimum research environment within budget

Performance bottom line...

- **Designed exhaust dispersion system**
  - For mission hazards
  - With priority for worker safety
  - That reduces stack-system life-cycle cost

Summary

- **Primary Issues**
  - Safety - Crucial reason for removal and dispersion of hazard
  - Temperature and humidity control – compliments HVAC system
  - Productivity of facility – supports mission
  - Cost to design; to Build; to Operate
- **Design Approach**
  - Standard practice
  - Good practice
  - Better practice

For More Information

Main Labs21 web site:

http://www.labs21century.gov

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